

THE NUTRITION OF THE HEART THROUGH THE VESSELS OF THEBESIIUS AND THE CORONARY VEINS.¹

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FEW beliefs of the present day are more firmly intrenched than that of the total dependence of the mammalian heart upon the coronary arteries. We are taught that without the blood brought by these vessels the long-continued, rhythmic contractions of the cardiac muscle are impossible. Such is the foundation on which rest in large part the prevailing ideas of infarction in the heart, with all the train of evil consequences believed to follow the embolism and thrombosis of the coronary arteries. It is my purpose to show that this doctrine is not absolute. The long-contracting, rhythmic heart is not wholly dependent upon the coronary arteries for its food supply; on the contrary, the heart will beat for hours while its arteries are empty. There are two ways in which the heart muscle may thus be nourished: the first, through the vessels of Thebesius, which open from the ventricles and auricles into a system of fine branches communicating with the cardiac capillaries; the second, through the coronary veins, which may convey a backward flow of blood from the auricle into the tissues of the heart.

So far as I have been able to determine, no experimental physiological work has ever before been done on the vessels of Thebesius; all opinion regarding their functional importance has rested upon the assumption that they serve only as veins, conveying a part of the venous blood from the coronary capillaries through the foramina Thebesii into the cavities of the heart. The question, too, of the nutritive significance of regurgitation from the auricle into the coronary veins has not apparently at any time been the object of investigation.

¹ The first account of these experiments was given to the American Physiological Society in May, 1897 (see *Science*, June 11, 1897). The subject was presented also to the Boston Society of Medical Sciences, June 1, 1897, and to the British Association for the Advancement of Science, Toronto, August, 1897.

The following pages will present an historical sketch of the anatomy of the vessels of Thebesius, and a record of my own anatomical studies of these vessels and of the coronary veins; a detailed account of my experiments on the nutrition of the heart through the vessels of Thebesius and the coronary veins will follow; and, finally, I shall endeavor to show that these forms of nutrition afford a reasonable explanation of the recovery of the heart from fibrillary contractions and from acute distentions leading to arrest, and of the extraordinary fact that hearts may work for years in spite of the almost complete obstruction of their arteries by advanced arterio-sclerosis.

I. THE ANATOMY OF THE VESSELS OF THEBESIIUS AND THE CORONARY VEINS.

The Vessels of Thebesius.—The discovery of the foramina Thebesii is credited to Vieussens;¹ but we owe the first accurate description of them to Thebesius,² whose valuable work, *De circulo sanguinis in corde*, was published by A. Elzevier in 1708. Nearly fifty years later we find Haller³ describing “still more, and much smaller, veins in the heart, whose little trunks, being very short, cannot easily be traced by dissection; and these open themselves by an infinite number of oblique small mouths, through all the numerous sinuosities observable on the surface of the right and left ventricle. These are demonstrated by injections of water, wind, or mercury, pushed into the coronary arteries, after you have first tied their corresponding or accompanying coronary veins; or even into the great coronary veins, after you have first intercepted the openings of their largest trunks. For, in either of these cases, there are drops of the tintured water, bubbles of air, spherules of mercury, rushing out through the whole extended surfaces of both ventricles of the heart; and this, without any violence that can be supposed sufficient to break the vessels. But the passage from the arteries into the cavities of the left side is more difficult.” Notwithstanding these various statements the existence of the vessels remained for many years a subject of dispute. Thus Abernethy⁴ early in the present century, commenting

¹ VIEUSSENS: *Nouvelles découvertes sur le cœur*; 1706; quoted by HALLER: *Elementa Physiolog.* Lausanne, 1757, lib. iv, p. 380.

² THEBESIIUS: *De circulo sanguinis in corde*. Leiden, 1708.

³ HALLER: *First lines of physiology*; English translation. Edinburgh, 1786, vol. i, p. 75.

⁴ ABERNETHY: *Philosophical Transactions*. London, 1798, p. 103.

on the perplexities of his predecessors, pointed out that even Haller, Senac, and Zinn were sometimes unable to discover the foramina, and were led to suspect that their apparently successful injections really ruptured the vessels and forced a way through false passages into the cavities of the heart. Abernethy himself made many injections, filling the arteries and veins with wax of different colors. He convinced himself that the foramina actually existed; and that they belonged moreover to both the arteries and the veins, because "the injection which was employed was too coarse to pass from one set of vessels to the other, and yet the different coloured injections passed into the cavities of the heart unmixed." His conclusion that some of the foramina communicate with coronary arteries is, I think, hardly to be accepted in the light of other observations. It is probable that in his experiments also extravasations took place from the arteries into the ventricles.

Bochdalek,¹ in 1868, published the results of observations on the foramina Thebesii of the auricles. He found in both auricles the mouths of small vessels. Many of these openings presented the appearance of blind depressions, since they were often covered with single valves in such a way as to resist investigation with the blowpipe. When he succeeded in introducing an injection-mass or a blast of air into a foramen, superficial, ramifying vessels were demonstrated, the injection of which often showed a connection with other foramina in the same auricle, or even in that of the other side. The foramina varied considerably both in number and in size; some were round and small; others were slit-like, resembling the mouths of the ureters; still others were large, round depressions, with smaller openings at the bottom. As a result of his observations, Bochdalek concludes "that the greater number of the small openings on the inner surface of the right as well as the left auricle, which from early times have borne the name of foramina Thebesii, represent the mouths of little veins that, often uniting into larger vessels, course with many branches through the auricular walls."

In 1880 appeared the report of Langer's² research on the foramina Thebesii of the human heart. With the aid of the blowpipe, and by means of a watery injection mass colored with Berlin blue, he demonstrated these foramina in all the cavities of the heart. He

¹ BOCHDALEK: Arch. f. Anat., Physiol. u. wiss. Med., Leipzig, 1868, p. 314.

² LANGER: Sitzb. der k. Akad. der Wissensch. zu Wien, 1880, Bd. lxxxii, 3. Abth., p. 25.

succeeded in injecting the vessels of Thebesius not only from the coronary vessels, but from the endocardial surfaces as well. Bochdalek's observations regarding the presence in both auricles of foramina Thebesii were thus confirmed, and the fact of a communication between the coronary vessels and each of the four cavities of the heart was thoroughly established. The foramina which Langer found on the endocardial surfaces of both ventricles were similar to those in the auricles, but much smaller. They were most conspicuous on the papillary muscles and in the neighborhood of the great vessels, being less easily seen in the region of the apex, where they were obscured by the trabecular network. Injections from the endocardial surfaces showed fine, ramifying vessels connected with the foramina, running either at right angles to the surface, or obliquely. From the fact that thick injection masses would not pass from the coronary veins into the ventricles, and that even watery masses were slow in appearing there, Langer concluded that the foramina Thebesii of the ventricles were not, as occasionally happens in the auricles, in direct communication with the coronary veins, but that they had to do with separate capillary areas. In no case did he observe valves in connection with the foramina Thebesii of the ventricles.

Gad¹ has recorded some confirmatory observations on the vessels of Thebesius in the ox. In the method which he describes for demonstrating the action of the valves of the left heart, wherein water under pressure is made to fill the ventricle and aorta, he noticed that water flowed into the right heart from the foramina Thebesii. On illuminating the interior of the left ventricle he was enabled to see fine, blood-stained streams, issuing from the endocardial wall into the clear water with which the cavity was filled.

Finally, Magrath and Kennedy,² working with artificial circulations of defibrinated blood on the isolated heart of the cat, observed that a small portion of the coronary blood found its way into the left ventricle. The only possible source of access, other than from the vessels of Thebesius, was leakage past the aortic valves. This leakage, as shown by a manometer record of the aortic pressure, did not occur.

Notwithstanding these painstaking observations, the vessels of Thebesius still occupy a very obscure position in anatomical literature. Foramina Thebesii are referred to as constant in the right

¹ GAD: *Arch. f. Physiol.*, 1886, p. 380.

² MAGRATH and KENNEDY: *Journ. of Exp. Med.*, 1897, ii, p. 13.

auricle, forming in part the mouths of small veins. Their occurrence in the left auricle is occasionally mentioned. But the fact that vessels of Thebesius open into all the chambers of the heart—ventricles as well as auricles—is hardly recognized.

The anatomical methods employed in the present study have been three in number; the injection of the vessels with air by means of the blowpipe, their injection with liquids, and the making of corrosion preparations. My experiments have in the main confirmed the results of other observers.

The initial step was to demonstrate independently the fact of a circulation in the vessels of Thebesius. By the injection of water, normal saline solution, or defibrinated blood, at a constant pressure, I established an artificial circulation through the coronary vessels of the fresh, often the still living, extirpated hearts of the rabbit and the dog. The cannula was tied directly into a coronary artery or one of its branches, so that access of liquid into the heart-cavities, except through the endocardial foramina, was rendered impossible. Yet liquid constantly found its way through the vessels of Thebesius. Thus I was enabled to verify the results of Magrath and Kennedy touching these vessels. It is essential to success that the heart be used before rigor has set in, and that the coronary system be thoroughly washed out by the injection of water or normal saline solution into the aorta. The following experiment will make the procedure clear.

February 8, 1897. A dog was anæsthetized with morphia and ether, and the heart excised after contractions had ceased. The coronary system was rinsed with normal saline solution introduced from the aorta. The systemic and pulmonary veins and the right coronary artery were ligated. A cannula was passed into the left coronary orifice from the aorta, and tied in the descending branch of the left coronary artery. The walls of the aorta were drawn close to the shank of the cannula by a ligature. Two outflow tubes were now arranged; one in the right ventricle through the pulmonary artery, the other in the left ventricle through the left auricular appendix. Normal saline solution colored with defibrinated blood was passed through the cannula under a constant pressure of 85 mm. Hg. and collected from each outflow tube separately. The amounts were then measured and compared. The quantity of the solution collected during five minutes was 400 cc. from the right ventricle, and 4 cc. from the left.

After thus assuring myself that a genuine communication exists between the coronary vessels and the left heart, it remained to in-

quire particularly into the nature of this communication. The heart of the ox was found best suited to the purpose. An examination of the endocardial surfaces of the ox heart reveals irregularly placed depressions, usually sharply outlined, varying widely in size, shape, and distribution. They are regularly larger in the auricles than in the ventricles. In the right auricle they may be provided with thin, single valves, especially about the origin of the great veins. In the left auricle they are usually fewer in number, and, so far as my observations have gone, unprovided with valves. Foramina Thebesii are never absent from the ventricles. In the right ventricle, which is especially well provided with them, the larger number are seen upon the septal wall. It is often much more difficult to find them in the left ventricle, although a diligent search is never without reward. Here, in agreement with Langer's statement, they often appear at or near the bases of the papillary muscles. They may present themselves in either ventricle almost anywhere on the endocardial surface. Structures, accessory to these ventricular foramina, which might in any way serve the office of valves, I have not seen; the edge of the foramen is usually sharply defined and may frequently exist as a partial, shelf-like covering, giving the impression, perhaps, of an attempt at a membranous valve; but it is seldom more than this.

Experience soon teaches one to distinguish, often at a glance, between the foramina Thebesii and merely blind depressions in the endocardium. On the injection of the vessels of Thebesius with air by means of the blowpipe applied to the foramina, characteristic, fine, sub-endocardial ramifications, which very frequently conduct the air into other Thebesian systems or even into the great coronary veins, will seldom fail to appear. Connection with the coronary veins may be further established by injection from the veins themselves. The following observations will illustrate these points.

April 7, 1897. — The right ventricle of a fresh ox heart was opened from the tricuspid valve to the apex. A large number of foramina were seen on the septal endocardial wall. The inflation with the blowpipe of vessels leading from these was in most instances followed by the appearance of air-bubbles at the mouth of the coronary sinus. On tracing the source of the bubbling, the air was observed to come from the mouth of a coronary vein at the extreme end of the sinus. This vein was now opened, and a cannula tied into the distal end. Defibrinated blood, forced through the cannula by blowing into the end of an attached rubber tube, was plainly seen to emerge from the foramina.

The ease with which injections of air and blood could be made to demonstrate the connection between the vessels of Thebesius and the coronary veins caused me to doubt the opinion expressed by Langer, that the foramina Thebesii in the ventricles communicate with the veins by capillaries alone. To settle this point I injected the coronary veins of the ox with starch and celloidin masses, both too thick to pass the capillaries, and found that even these emerged from the foramina Thebesii of the right ventricle. So intimate a connection, however, between the coronary veins and the vessels entering the left ventricle I have not yet been able to demonstrate.

By means of a very successful corrosion preparation, made by injecting the veins of an ox heart with celloidin, I was able to trace the communication. In this preparation the position of some of the foramina Thebesii was marked by small discs of the hardened mass, formed by the oozing out of the celloidin upon the endocardium. These foramina were shown to be connected with the smaller coronary veins by fine branches. The still finer ramifications which, as Langer has demonstrated, lead from the foramina and branch directly into capillaries were here uninjected; they would appear only when injected from the foramina themselves.

Although I have made attempts, I have been unable to discover anything more free than a capillary connection between the vessels of Thebesius and the coronary arteries. Injections of starch or celloidin fail to pass from the arterics into the cavities of the heart.

Bochdalek's observation, relative to a communication between the auricles through vessels of Thebesius, I have verified on the heart of the dog. Blowpipe injection of a foramen in the left auricle caused an exit of air from a similar foramen in the right auricle, and this without any discernible inflation of a coronary vein.

I have no reason to believe that any of my results have been due to the rupture of vessels and the consequent extravasation of the circulation-fluid or injection-mass. Care has been taken throughout to avoid high pressures, and this, together with the very important consideration that my material has all been fresh, would serve to render errors resulting from this cause very improbable.

The vessels of Thebesius, therefore, open from the ventricles and auricles into a system of fine branches that communicate with the coronary arteries and veins by means of capillaries, and with the veins — but not with the arteries — by passages of somewhat larger size.

The Coronary Veins. — Whenever in my experiments a circulation-fluid has been permitted to gain access to the coronary sinus from the right heart, the anatomical possibility of a back-flow into the veins has been demonstrated. I have taken pains to supplement these observations with dissections of the coronary veins in the cat, dog, and ox. Everything has pointed to the fact that such valves as the veins of the heart possess are very inefficient. A single membranous fold is usually found at the entrance of a vein into the sinus; seldom does it prevent the entrance of air or liquids. Valves at the confluence of venous branches I have found either wanting or very poorly developed. The Thebesian valve at the mouth of the coronary sinus is totally insufficient to prevent regurgitation.

II. THE NUTRITION OF THE HEART THROUGH THE VESSELS OF THEBESIUS.

The experiments which I shall now describe were suggested by the possibility of an arterial function on the part of the vessels of Thebesius. They have served to prove not only that these vessels may carry nutriment to the heart-muscle, but that in the absence of all other forms of cardiac nutrition — with the blood-supply through the coronary arteries absolutely cut off — the mammalian ventricle may be maintained, under proper conditions, in rhythmic contractions lasting several hours.

Nearly all of the experiments have been made upon the heart of the cat. The animal is anæsthetized with ether, tracheotomized, and bled from a cannula tied into a carotid artery. The blood is defibrinated and filtered through glass wool. On cessation of the bleeding the ventral chest wall is at once removed by cutting through the costal cartilages, and the heart quickly severed from its connections. If care has been taken with the etherizing, respiration should have persisted up to the time of opening the thorax, and the excised heart should be beating with perfect regularity; fibrillary contractions need not, however, interfere with success. The heart is rinsed in warm normal saline solution. A cannula about the size of the aorta is now introduced into the right ventricle through either the auricle or the pulmonary artery, and secured by a ligature passed tightly around the base of the heart in a line parallel to the auriculo-ventricular groove and below the coronary sinus. Thus a fluid introduced into the ventricle through the cannula can find no outflow except through the vessels of Thebesius. The cannula is now supported in an

upright position, with the heart suspended from the lower end, and the defibrinated blood poured in until the ventricle is full and the blood rises in the tube to a height of several inches. Figure 1 will make clear the relation of the cannula to the ventricular cavity. Figure 2 represents a form of perfusion cannula and a heating apparatus which have been found very convenient for supplying fresh blood constantly to the ventricle, and for maintaining the heart at body-temperature.



FIGURE 1. Diagram to illustrate the mode of securing the cannula in the ventricular cavity for nutrition through the vessels of Thebesius.

As a result of the above method — often within a minute after the introduction of blood — strongly marked, regular, coördinated contractions of the ventricle are observed. With a periodic supply of fresh blood, and with favorable temperature and moisture, this activity may continue several hours. The following are typical experiments.

April 1, 1897. An etherized cat was tracheotomized and bled from the left carotid artery. The heart was excised while beating, and rinsed in saline solution. A cannula was passed into the right ventricle through the right auricular appendix, and secured by a ligature tied tightly about the base of the heart. The heart had fibrillated immediately after excision, and shortly had ceased all movement. The cannula and the ventricle were now filled with defibrinated blood diluted with one part saline solution. The ventricle straightway began to beat with great regularity. On suspension of the heart in saline solution of normal temperature the beat was increased in frequency. The blood, rising in the tube about 15 mm. with each beat, became gradually venous in color. The frequency of contraction then diminished, but was restored by replacing the venous with arterial blood. No diminution in the amount of the blood was noticeable, and no blood could be seen to issue from the heart. The coronary arteries were empty; the veins were filled over the entire surface. Tracings were taken by attaching a rubber tube connected with a Marey tambour to the top of the cannula (Fig. 3). The resistance thus occasioned gradually lessened the frequency of the heart-beat, but the heart immediately recovered its former rate on removal of the tambour-tube.

The heart began beating at 4.55 P. M. At 6.20 it was still beating slowly. The blood had been renewed several times.

An experiment of April 2, 1897, showed that a true circulation may take place between the vessels of Thebesius and the coronary veins. Here the conditions were the same as in the experiment just

recorded, except that two of the veins were incised. A small but steady stream of venous blood issued from them.

On April 3, under the same conditions, the descending branch of the left coronary artery was opened. No flow of blood occurred from the artery, although there was a free escape from an incision in an accompanying vein.

The following experiment shows that the above form of nutrition is not confined to the right ventricle.

April 7, 1897. The left ventricle of a cat was nourished with blood by the same method, except that the trunks of both coronary arteries were ligated, and the ligature about the ventricles omitted. The supply cannula was tied into the ventricle through the aorta. On the introduction of blood the left ventricle alone began to beat strongly and regularly. The height of the blood column was about 80 mm. A small but continuous flow of blood occurred from a cut vein. The beating continued for over an hour, becoming weak at last, but remaining regular. The blood found its way in part into the right ventricle, coming of necessity through the walls. The blood had been changed frequently by perfusion, and had invariably become venous in color. The temperature was kept at 30–36° C.

In considering these experiments the suspicion very naturally arises that the prolonged contractility of the filled ventricle may be due, not to the nutritive property of the blood, but to mere mechanical stimulation brought about by distention. Evidence that such distention is in itself a powerful stimulus to contraction has recently been furnished in this Labo-

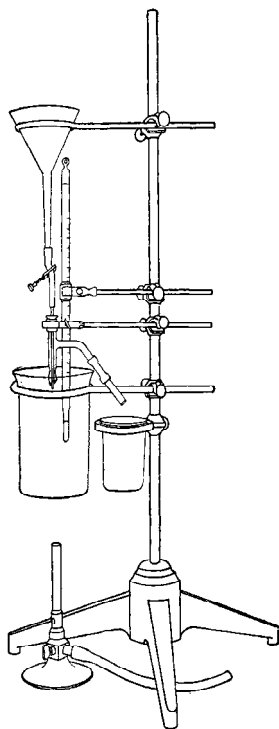


FIGURE 2. Perfusion apparatus for feeding from the interior of the heart-cavities. Blood placed in the funnel is allowed to pass very slowly through the fine glass tube into the ventricle, which is tied upon the cannula as illustrated in Figure 1. The supply is regulated by the compression clamp. Each beat of the ventricle forces the blood back through the space between the fine inner tube and the walls of the cannula, out through the side branch, and thence into the small receiving beaker. The large beaker is filled with saline solution kept at normal temperature.

ratory.¹ But mechanical stimulus is inadequate to explain the phenomenon; for when Ringer's solution of sodium, potassium, and calcium chlorides² is used alternately with blood under constant conditions, the solution fails to sustain contractions, while the blood succeeds. The following experiment is an example.

April 10, 1897. A cat's heart was prepared in the usual way, with the cannula in the right ventricle. Ringer's solution at 35° C. was now introduced instead of blood. A slow beating of the right ventricle began: during the first five minutes, 30 beats; during the second five minutes, 6 beats. The contractions were at first strong, but gradually became irregular in force, and spasmodic; they finally stopped. During a third five minutes there were no beats. The solution was now replaced by blood. The beating returned: during the first five minutes, 44 beats; during the second five minutes, 174 beats (60 during the last minute). The contractions were strong and regular throughout fifteen minutes; and later, when the blood was removed and the ventricle washed out, were still seen.

An immediate repetition of the above procedure was followed with similar results; Ringer's solution failed to sustain contractions, while blood caused long-continued beating.

There can remain, then, no doubt of the genuinely nutritive character of the phenomena observed under this method; for the blood enters the ventricle as arterial blood and emerges into the veins of a dark venous color, while rhythmic beats are maintained for a much longer period than can be accounted for on other grounds. Since all other possible channels have been cut off, the veins, which fill with blood, can communicate with the ventricle only by means of the vessels of Thebesius. The coronary arteries can take no part in the circulation, since they are found empty.

One of the conspicuous features in the experiments of Magrath and Kennedy was the fact that an exceedingly small blood-supply was sufficient to maintain the unloaded heart of the cat in regular contractions. These authors published a graphic record of excellent beats which were sustained by a coronary circulation of about 3.3 c.c. per minute, and report a case of fair contractions observed under a circulation of less than 2 c.c. per minute; the customary volume

¹ HYDE (I. H.): Proceedings of the American Physiological Society, Science, Jan. 22, 1897. The paper will be published in full in this Journal, 1898, vol. i.

² Modified for mammalian tissues: NaCl, 0.9%; CaCl₂, 0.02%; KCl, 0.01%; water distilled in glass. The formula was kindly furnished by Mr. F. S. Locke.

employed ranged from 3.5 c.c. to 13 c.c. per minute. My own results serve to emphasize this fact still further. In supplying the heart with blood through the vessels of Thebesius the circulation was at all times very small—in many cases, even, hardly measurable. In the experiment of April 1, there can have been scarcely more than a mere oozing of blood in and out between the coronary veins and the ventricular cavity through the vessels of Thebesius.

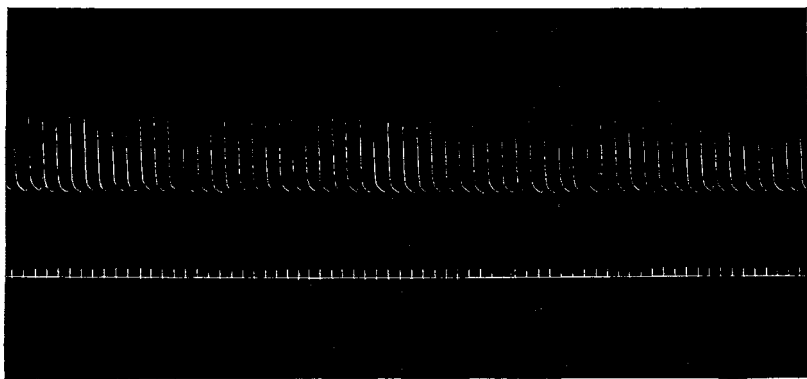


FIGURE 3. From a cat's heart fed from the interior of the right ventricle, April 1, 1897. Recorded one hour after removal of the heart from the body. The upper curve was drawn by means of a Marey tambour connected with the cannula in the right ventricle. The lower curve gives the time in seconds.

The discussion of the nutrition of the heart through the vessels of Thebesius leads now to the consideration of a somewhat striking analogy. It is known that the heart of the frog receives almost its entire nutriment through the branching passages that carry the blood from the interior of the heart nearly to the pericardial surface. My experiments have shown that the heart of the cat may be nourished in much the same way; there is, indeed, a marked resemblance in both method and results between my experiments and many which have heretofore been performed on the heart of the frog. The simplicity of this method of nutrition, as well as its value in bringing the mammalian and batrachian hearts in a physiological sense closer together, seems to assure its further usefulness in experimental work.

III. THE NUTRITION OF THE HEART THROUGH THE CORONARY VEINS.

The possibility of a nutrition through a back-flow from the auricle into the coronary veins was first suggested by an experiment per-

formed April 5, in which the right ventricle was prepared in the usual way, except that the ligature encircling the heart was omitted. The cannula was tied into the pulmonary artery. Blood was thus allowed to enter the right auricle through insufficiency of the tricuspid valve. The heart was sustained in rhythmic contractions for eight hours,—a period considerably in excess of that observed in nutrition through the vessels of Thebesius alone. It was inferred that

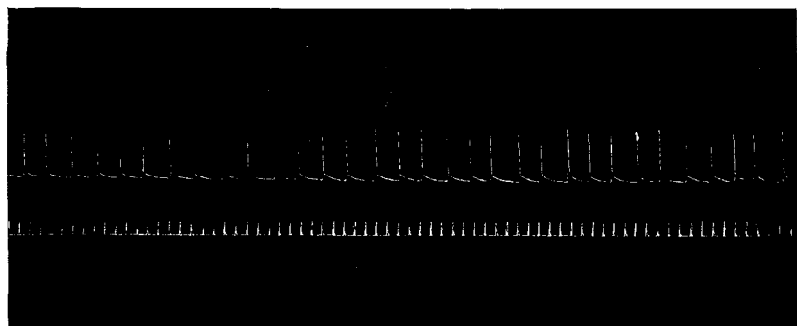


FIGURE 4. From a cat's heart fed from the right ventricle and auricle, April 5, 1897. Recorded six hours after the removal from the body and the beginning of contractions. The upper curve was drawn by means of a Marey tambour connected with the cannula in the pulmonary artery. The lower curve gives the time in seconds.

blood had gained access from the auricle to the coronary veins, and had thus aided materially in the nutrition. The question was therefore submitted to experiment, as follows:—

June 26, 1897. The coronary sinus of a freshly extirpated cat's heart was opened at its middle, and a cannula tied into the distal end. This cannula was supported vertically, and filled to a height of 12 cm. with defibrinated arterial blood. A few minutes after the introduction of the blood both ventricles began to beat. The contractions were coördinated, regular, and complete, and took place at intermittent periods for an hour and a half; they were facilitated by frequent renewals of the blood. The amount of blood contained in the cannula was never more than 4 c.c. During the experiment numerous recoveries from fibrillary contractions were observed, and records secured during the process of recovery. (Fig. 5.)

The above experiment makes evident the fact that under very low blood-pressure the unloaded heart may be made to beat for a long time by feeding it through the coronary veins alone.

IV. THE IMPORTANCE OF NUTRITION THROUGH THE VESSELS OF THEBESIIUS AND THE CORONARY VEINS IN CERTAIN PATHOLOGICAL STATES OF THE HEART.

There are three pathological states upon which the modes of nutrition under discussion appear to have an important bearing; namely, fibrillary contractions, arrest of the heart without fibrillation, and arterio-sclerosis of the coronary arteries.

The recovery of the cat's heart from fibrillary contractions has already been mentioned in the description of my experiments of April 1 and June 26. In one of these the heart was fed from the

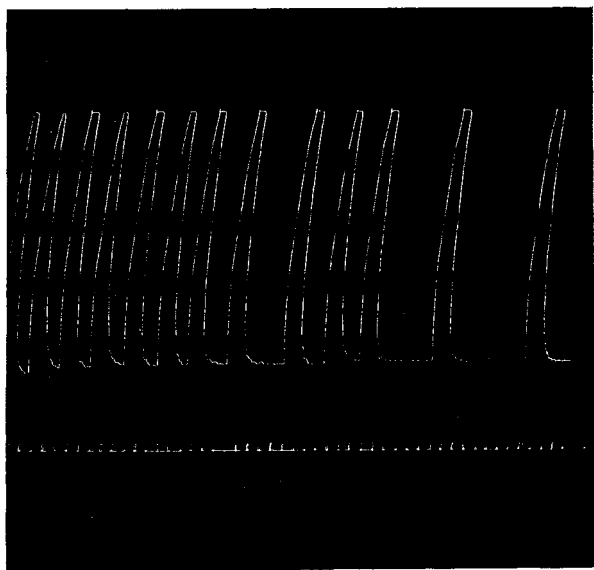


FIGURE 5. Curve drawn immediately after marked fibrillary contractions, by an ordinary muscle lever attached to the apex of a cat's heart fed through the coronary sinus, June 26, 1897. The fibrillation took place one hour after excision of the heart, and lasted two minutes. The lower curve marks the time in seconds.

ventricle through the vessels of Thebesius; in the other, from the coronary sinus through the coronary veins. It is probable that nutrition through these channels is of great value to the struggling heart, both in preventing fibrillation, and possibly in recovering the heart after fibrillation has set in. That such a recovery may occur, even in the dog, has recently been demonstrated by MacWilliam¹

¹ MACWILLIAM: *Journ. of Physiology*, 1887, viii, p. 299.

and Porter.¹ There is therefore no ground for denying the possibility of recovery in the human heart, although it is likely enough that such instances are extraordinarily rare; and if the cat's heart can be recovered by feeding through the vessels of Thebesius or the coronary veins, the importance of these modes of cardiac nutrition in the fibrillar contractions of the hearts of other mammals can hardly be gainsaid.

It should be remarked that the heart in the living animal is, during fibrillation, in a state particularly favorable to nutrition through both the vessels of Thebesius and the coronary veins. Measurements taken in the left ventricle show that the intracardiac pressure rises as fibrillation draws near,² so that the heart is greatly distended even before it has ceased to beat. The arrest of the ventricle lowers the blood-pressure in the aorta, and hence the blood-pressure in the smallest peripheral coronary arteries, to almost nothing. Consequently the passage of the blood through the vessels of Thebesius and the regurgitation from the auricle through the coronary veins are doubly aided; on the one hand by the relatively high pressure in the ventricle and auricle, and on the other by the diminished resistance in the coronary vessels. I have already demonstrated how slight a pressure will drive the blood from the interior of the ventricle or auricle through the cardiac walls. The intracardiac pressure at the onset and in the earlier moments of fibrillation would seem to be more than sufficient to establish such a circulation, giving the quivering organ one chance of recovery, although a desperate chance at best.

In simple arrest of the heart without fibrillation the nutrition through the vessels of Thebesius and the coronary veins may work to great advantage. Here once more the heart is distended; here again the pressure in the coronary arteries has fallen very low; but no fibrillation dissipates the energy of the cardiac muscle in futile, uncoordinated contractions. The occasional recovery of these arrested hearts can scarcely be explained by the theory that leaves the heart un-nourished save through the coronary arteries. It is the pressure in the aorta that drives the blood in the coronary arteries into the cardiac walls in spite of the peripheral resistance. The aortic pressure is maintained by the beat of the ventricle; the loss of a few successive beats lowers it enormously: the reservoir receives

¹ PORTER: This Journal, 1898, i, p. 71.

² PORTER: Journ. of Physiol., 1894, xv, p. 133.

nothing, and is speedily drained through the smaller arteries into the capillaries and veins. The coronary capillaries receive their portion with the rest; but whence shall they get more? The pressure in the aorta has fallen, but the peripheral resistance in the coronary system still remains. The power that drove the blood through this resistance is gone, and the capillary areas once fed through the coronary arteries are thereby closed; they can be opened only by the forcible contraction of the left ventricle. But the ventricle lies passive; and should remain so, according to the prevailing belief that the heart is self-nourished and must beat or starve. It is here that the nutrition through the vessels of Thebesius and the coronary veins becomes of importance. The heart *is* self-nourished, but not through its arteries alone; the prostrate ventricle, although it has ceased to feed itself through the coronary arteries, can still be fed by the blood that distends its cavities, and by this endocardiac nutrition may gather strength to resume its load.

Still more interesting is the relation of endocardiac nutrition to arterio-sclerosis of the coronary arteries. The pathologist often finds the coronary arteries thick and stiff with calcareous deposits, their lumen greatly reduced or even wholly gone. And when he looks for the infarcts that should have followed the blocking of the terminal artery, he sometimes sees none. The area formerly supplied by the closed artery is occasionally apparently healthy. Life has continued for months or even years with what seems an impossible heart. No wonder that many anatomists and physicians still contend in the face of conclusive experiments that the coronary arteries are not truly "terminal." How else can such immunity from infarction be explained? What but a collateral circulation through branches freely communicating with other coronary arteries could have kept the ever active muscle from decay? The failure of the distal end of a severed coronary artery to bleed in the profuse way that indicates a free communication with other vascular areas; the fact that infarcts frequently, though not invariably, follow the embolism or thrombosis of these vessels during life; and, most conclusive of all, the easy production of infarcts by the ligation of coronary arteries,¹ — have not convinced some minds. They cling to the occasional freedom from infarction after thrombosis or embolism, and not seldom attempt to strengthen their position by

¹ KOLSTER: *Skandinav. Arch. f. Physiol.*, 1893, iv, p. 1; also PORTER, *Arch. f. d. ges. Physiol.*, 1893, lv, p. 366.

pointing to the fact that one coronary artery can be injected from another.

These writers forget what a terminal artery really is. They forget that terminal arteries, like all other blood-vessels, communicate with their neighbors by capillaries. An artery is terminal, not because it has no communication with neighboring arteries, but because this communication is of a particular kind. "Terminal" means simply that the resistance in the anastomosing branches is greater than the blood-pressure in the arteries leading to these branches. It is this resistance which makes the artery terminal. The concept is physiological, and only secondarily anatomical. The fact that an artery can be injected post-mortem from another artery is no evidence that the living blood in the living organ follows the course of the post-mortem injection. The natural relation between the blood-pressure in the arterioles and the resistance in the communicating vessels cannot be imitated with accuracy. Only injections that pass with great ease can be used as presumptive evidence against the terminal nature of the artery; and, as a fact, aside from rare abnormal cases, injections pass from one coronary artery to another with difficulty or not at all. The advocates of the free anastomosis of the coronary arteries have indeed a difficult position. They must explain how infarcts can follow the closure of freely anastomosing vessels. We who believe in the terminal nature of these arteries need only explain why the closure occasionally fails to produce infarction. And this explanation can now be given.

A certain small number of the cases in which closure fails to produce infarction must be ascribed to the abnormal anastomoses that are occasionally present. It is possible also that the very gradual closure of an artery might permit the gradual dilatation of the communicating vessels until the resistance in them is low enough to divert a part of the blood in the neighboring areas into the anæmic district, and thus gradually establish sufficient collateral circulation to keep the part alive. These possibilities have long been recognized.

A new and effective mechanism for the rescue of the cardiac muscle from threatened infarction is found in the nutrition through the vessels of Thebesius and the coronary veins. Through these ever present channels blood can be drawn to the anæmic area for the occasional saving of hearts in which the blocking has been sufficiently slow. Usually, however, the blood must find the resist-

ance in the arterial capillaries too great to be overcome, and will fail to prevent infarction.

It is evident that the nutrition through the vessels of Thebesius and the coronary veins must modify in no slight degree the existing views of the nutrition of the mammalian heart, and of the manner in which infarction of the heart takes place.

This work was undertaken at the suggestion of Dr. W. T. Porter. I wish, in concluding, to express my grateful appreciation of his encouragement and aid.

SUMMARY.

(1) The vessels of Thebesius open from the ventricles and auricles into a system of fine branches that communicate with the coronary arteries and veins by means of capillaries, and with the veins — but not with the arteries — by passages of somewhat larger size.

(2) These vessels are capable of bringing from the ventricular cavities to the heart-muscle sufficient nutriment to maintain long-continued, rhythmic contractions.

(3) The heart may also be effectively nourished by means of a flow of blood from the auricle back into the coronary sinus and veins.

(4) Nutrition through the vessels of Thebesius and the coronary veins contributes to the recovery of the heart from fibrillary contractions and from simple arrest without fibrillation, and affords a reasonable explanation of many cases in which the cardiac tissues have survived for months or even years the closure of terminal arteries long believed to be their sole supply.